CTEQ GLOBAL QCD ANALYSIS

* PDFs for showering programs
* PDFs with a variable QCD coupling

Pavel Nadolsky

Southern Methodist University
Dallas, TX, U.S.A.

in collaboration with

J. Huston, M. Guzzi, H.-L. Lai, Z. Li, S. Mrenna, J. Pumplin,
D. Stump, W.-K. Tung, and C.-P. Yuan

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CTEQ-Tung Et Al.: ongoing activities

- **PDFs for leading-order Monte-Carlo programs** ***(arXiv:0910.4183)***
- **Uncertainty in α_s in the CTEQ PDF analysis** ***(arXiv:1004.4624)***
- General-purpose NLO PDF fits
  - CTEQ6.6 set (published in 2008)$\longrightarrow$ CT09 (not released) $\longrightarrow$ CT10 (pre-released within CTEQ)
  - combined HERA and Tevatron Run-2 lepton asymmetry data are included
  - new statistical methods and parametrization forms
- Benchmarking of heavy-quark contributions

  2009 Les Houches Proceedings
- Constraints on color-octet fermions *(with Berger, Guzzi, Olness)*
- Exploration of statistical methods and PDF parametrizations *(Pumplin, arXiv:0909.0268 and 0909.5176)*

CT09MC PDF's for leading-order Monte-Carlo generators at the LHC

Lai, Huston, Mrenna, P. N., Stump, Tung, Yuan, JHEP 1004, 035 (2010)

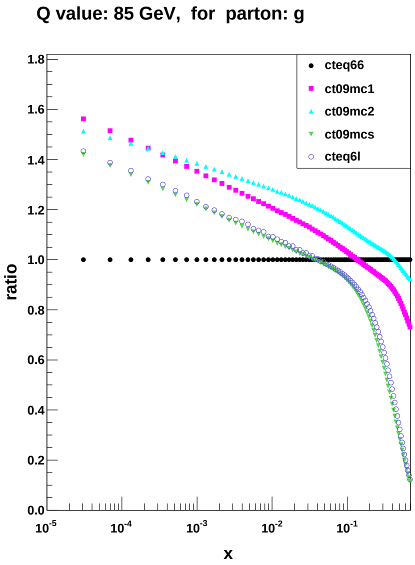
Related studies: Sherstnev, Thorne, arXiv:0711.2473; Jung, Sjostrand @ the HERA-LHC workshop

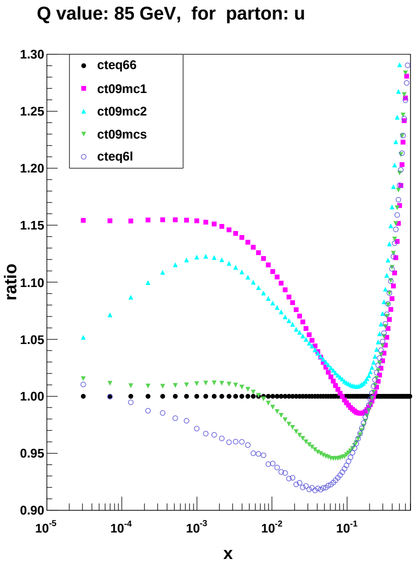
- **Leading-log** showering programs (PYTHIA, HERWIG,...) will remain ubiquitous tools in the observable future
- We wish to construct improved PDFs for showering programs **at the LHC**, to be used when NLO calculations (with or without showering) are not applicable for some reason
- These PDFs do not have to be "strictly at leading order", because showering introduces contributions beyond LO

Requirements for LO-MC PDFs

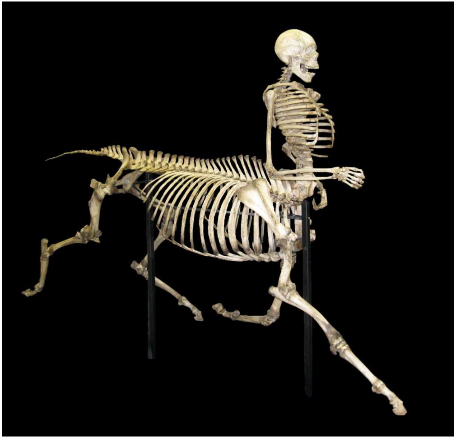
- **LO** DGLAP evolution
- Steep **LO** gluon PDF $g(x, Q)$ at small x, required by models of underlying event
- when combined with LO matrix elements, **reproduce NLO rapidity distributions for key LHC processes** (production of $W^{\pm}$, Z^0, H^0...)
- $\Rightarrow$ are about the same as NLO PDFs at large x, or exceed them

Resulting PDFs at $Q = 85$ GeV





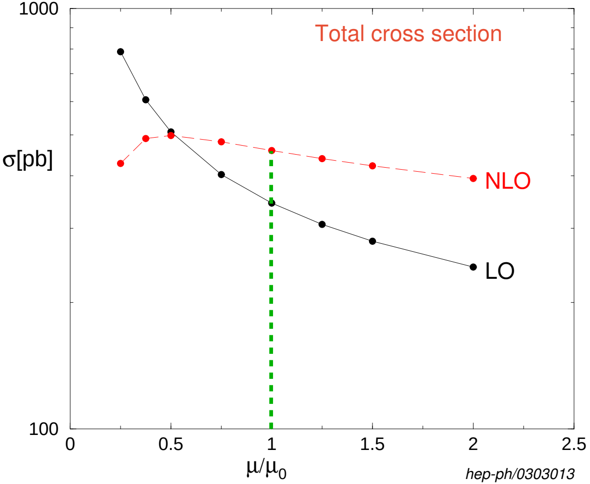
Is this liminal creature viable?



Let's examine the bones, focusing on fixed-order cross sections.

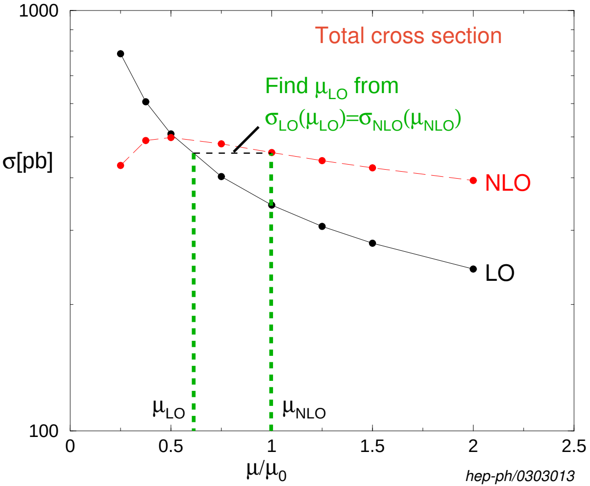
Modifications by parton showering (in PYTHIA) are smaller than the dependence on PDFs ($\Rightarrow$backup slides)

Approximating NLO cross sections by LO cross sections



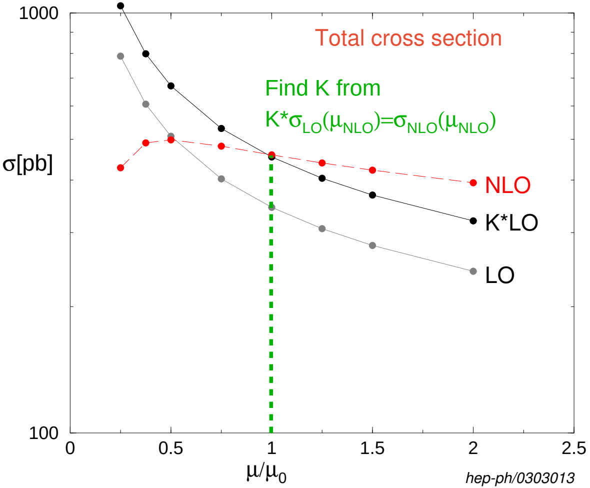
- NLO cross sections: more predictive
- LO cross sections: more uncertain (=flexible)

Approximating NLO cross sections by LO cross sections



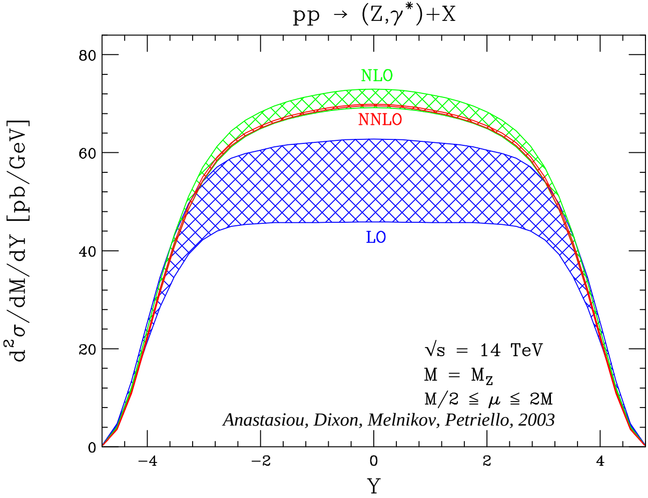
Option 1: Optimize the factorization scale μ_{LO}

Approximating NLO cross sections by LO cross sections



Option 2: Optimize the factor $K = \sigma_{NLO}(\mu_{NLO})/\sigma_{LO}(\mu_{NLO})$ (i.e., the floating normalization of σ_{LO})

Approximating NLO cross sections by LO cross sections



For $d\sigma_{NLO}/dy$, etc.,optimize **both** μ_{LO} and K to reproduce normalization and shape

CT09MC PDFs: selection of data

- Perform a **LO** fit to
  - CTEQ6.6 set of experimental data from DIS, production of vector bosons and jets (2700 points)
  - **pseudodata** at $\sqrt{s} = 14$ TeV, containing **NLO predictions** probing typical combinations of PDFs at various (x, Q):
    - $d\sigma/dy$ for $pp \to W^{\pm}X$, $pp \to Z^0 X$, $pp \to H^0 X$; $d\sigma/dM_{t\bar{t}}$ for $pp \to t\bar{t}X$; $d\sigma/dM_{b\bar{b}}$ for $gg \to b\bar{b}$ at $M_{b\bar{b}}$ of 10-50 GeV

All cross sections are at fixed order; modifications by showering are examined outside of the fit

Vary K_i and/or $\mu_{LO,i}$ in the fit

Three CT09MC PDF sets

PDF set	CT09MCS	CT09MC1	CT09MC2
$\mu_{LO,i}$	Varied	Fixed	Fixed
K_i	Varied	Varied	Varied
Loops in α_s	2	1	2
Momentum sum rule	enforced	relaxed	relaxed

- relaxation of the momentum sum rule *(Sherstnev, Thorne)* by 10-15% produces a more flexible $g(x,\mu)$, smaller $K_i - 1$

Reconciling LO with the global data

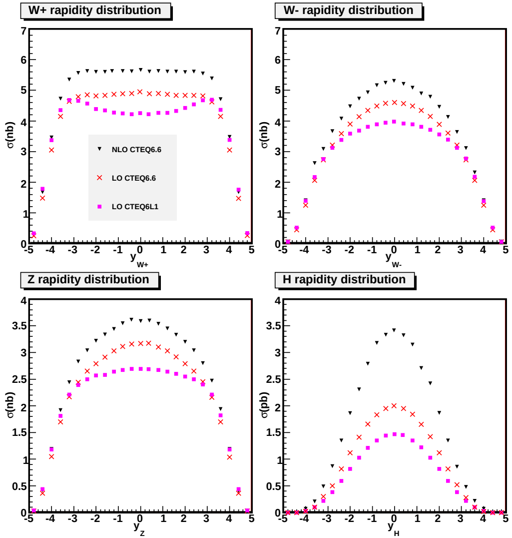
- $\chi^2/d.o.f.$ is worse at LO than at NLO by 20-30%
- When the (mostly high-Q) LHC pseudodata are included, the agreement with the (mostly low-Q) real data deteriorates

Therefore:

- pseudodata errors (χ^2 weights) are chosen to balance between the agreement with the real data and pseudodata
- two-loop α_s improves χ^2
- Variable $\mu_{LO,i}$ and K_i improve χ^2
- relaxed momentum sum **slightly** improves χ^2

$d\sigma/dy$ for conventional LO PDFs

LO ME-LO PDF (CTEQ6L1) vs. LO-NLO (CTEQ6.6M) vs. NLO-NLO (CTEQ6.6M)

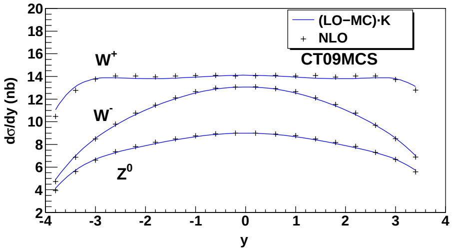


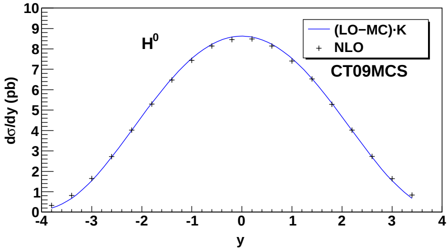
- Significant differences in normalizations and shapes between LO-CTEQ6L1 and LO-CTEQ6.6M predictions
- Unphysical forward-backward peaking in the LO-CTEQ6L1 $d\sigma/dy$ for W^+ production

CT09MCS (scale) set

Two-loop $\alpha_s(\mu)$; vary μ and K; enforce momentum sum

Agreement with normalization and shape of NLO cross sections

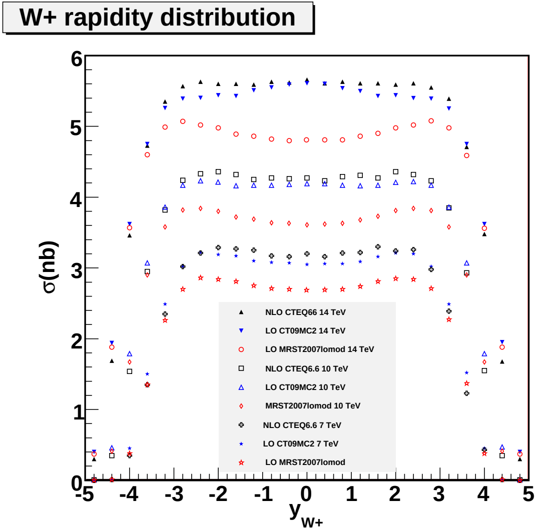




	W^+	W^-	Z	H	$t\bar{t}$	$b'\overline{b'}$
μ_i	1.96 M_W	1.96 M_W	1.96 M_Z	1.06 M_H	1.41 M_t	0.40 $M_{b'\overline{b'}}$
K_i	1.11	1.09	1.09	1.87	2.09	4.09

CT09MC1 and 2 sets

One- and two-loop $\alpha_s(\mu)$; vary μ and K; relax momentum sum



Best-fit K factors

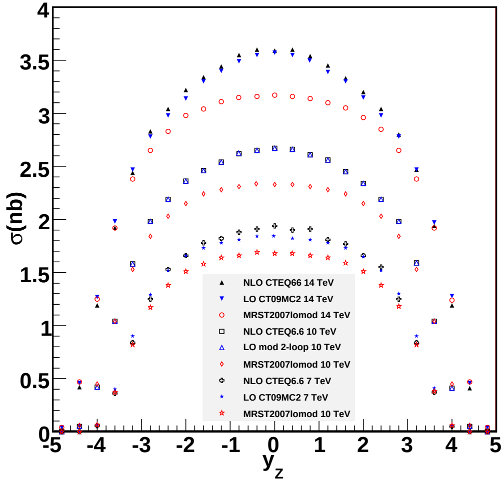
	MC1	MC2
W^+	1.00	1.02
W^-	0.99	1.00
Z^0	0.98	1.00
H^0	1.22	1.32
$t\bar{t}$	1.09	1.09
$b'\bar{b}'$	2.70	3.13
mom. sum	1.10	1.14

LO cross sections are plotted without K factors

CT09MC1 and 2 sets

One- and two-loop $\alpha_s(\mu)$; vary μ and K; relax momentum sum

Z rapidity distribution



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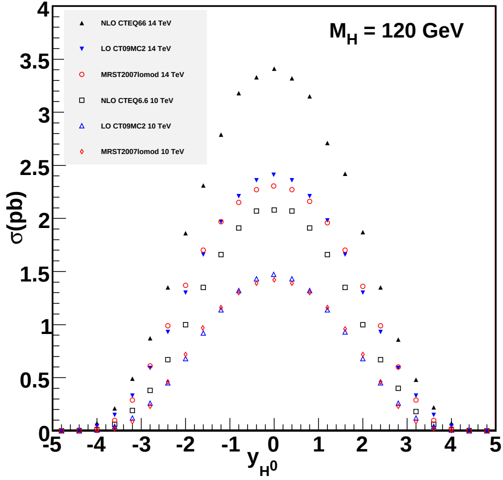
LO cross sections are plotted without K factors

CT09MC1 and 2 sets

One- and two-loop $\alpha_s(\mu)$; vary μ and K; relax momentum sum

SM Higgs boson rapidity distribution



Best-fit K factors

	MC1	MC2
W^+	1.00	1.02
W^-	0.99	1.00
Z^0	0.98	1.00
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$t\bar{t}$	1.09	1.09
$b'\bar{b}'$	2.70	3.13
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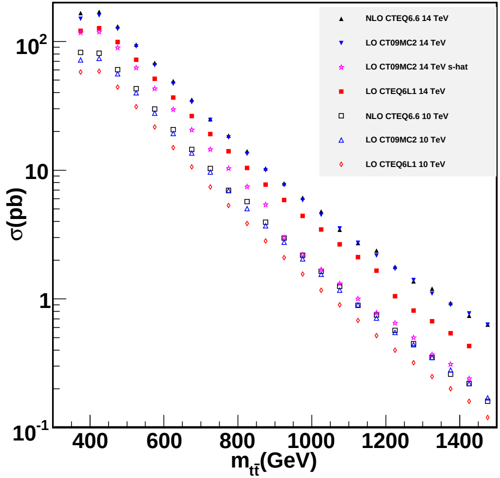
LO cross sections are plotted without K factors

CT09MC1 and 2 sets

One- and two-loop $\alpha_s(\mu)$; vary μ and K; relax momentum sum

$t\bar{t}$ mass distribution



Best-fit K factors

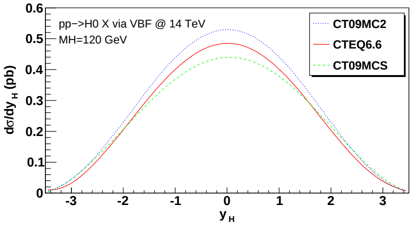
	MC1	MC2
W^+	1.00	1.02
W^-	0.99	1.00
Z^0	0.98	1.00
H^0	1.22	1.32
$t\bar{t}$	1.09	1.09
$b'\bar{b}'$	2.70	3.13
mom. sum	1.10	1.14

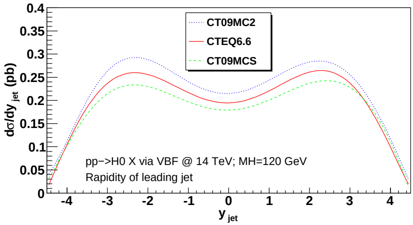
LO cross sections are plotted without K factors

CT09MC approximation for other LHC cross sections...

... may or may not be not adequate in general, depending on the similarity to the fitted cross sections

...works reasonably well for $pp \to H^0 X$ via vector boson fusion, for a few other examined processes





Uncertainty in α_s in the CTEQ6.6 and CT10 PDF analysis

arXiv:1004.4624

- Two leading theoretical uncertainties in LHC processes are due to α_s and the PDFs
- These are not independent uncertainties; how can one quantify their correlation?
- Which central $\alpha_s(M_Z)$ and which error on $\alpha_s(M_Z)$ are to be used with the existing PDFs?
- What are the consequences for key LHC processes ($gg \to H^0$, etc.)?

Uncertainty in α_s in the CTEQ-TEA PDF analysis
arXiv:1004.4624

Recent activity to examine these questions, e.g.:

- **MSTW** *(arXiv:0905.3531)*
  - $\alpha_s(M_Z)$ is an **output** of the global fit (constrained by the hadronic scattering only)
  - several sets of error PDFs, each with its own $\alpha_s(M_Z)$ value $\Rightarrow$ lengthier calculations
  - The α_s uncertainty and PDF uncertainty are inseparable
- **NNPDF** *(in 2009 Les Houches Proceedings, arXiv:1004.0962)*:
  - $\alpha_s(M_Z) = 0.119 \pm 0.002$ is taken as an **input**
  - α_s-PDF correlation is examined with ~ 1000 PDF replicas and found to be small
- **H1+ZEUS** *(arXiv:0911.0884)*: sensitivity of the HERAPDF set to $\delta\alpha_s(M_Z) = \pm 0.002$ is explored

CTEQ6.6FAS analysis

- Take the "world-average" $\alpha_s(M_Z) = 0.118 \pm 0.002$ as an **input**:

$$\alpha_s(M_Z)|_{\text{in}} = 0.118 \pm 0.002 \text{ at } 90\% \text{ C.L.}$$

- Find the theory parameter $\alpha_s(M_Z)$ as an **output** of a global fit (CTEQ6.6FAS):

$$\alpha_s(M_Z)|_{\text{out}} = 0.118 \pm 0.0019 \text{ at } 90\% \text{ C.L.}$$

- The combined PDF+α_s uncertainty is estimated as

$$\Delta X = \frac{1}{2}\sqrt{\sum_{i=1}^{22+1}\left(X_i^{(+)} - X_i^{(-)}\right)^2}$$

- **Problem:** each PDF set comes with its own $\alpha_s \Rightarrow$ cumbersome
- **A simple workaround exists!**

A quadrature sum reproduces the α_s-PDF correlation

H.-L. Lai, J. Pumplin

Theorem

In the quadratic approximation, the total α_s+PDF uncertainty $\Delta\sigma$ of the CTEQ6.6FAS set, with all correlation, reduces to

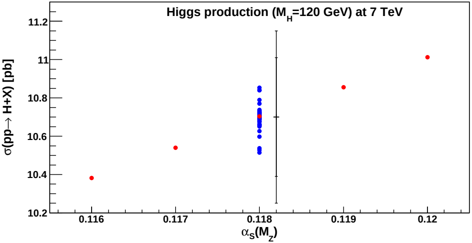
$$\Delta X = \sqrt{\Delta X^2_{CTEQ6.6} + \Delta X^2_{\alpha_s}},$$

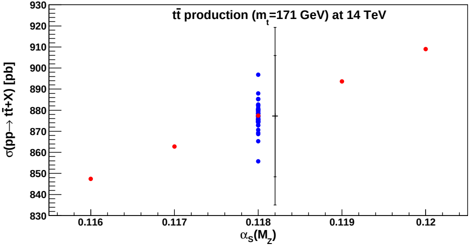
where

- $\Delta X_{CTEQ6.6}$ *is the CTEQ6.6 PDF uncertainty from 44 PDFs with the same* $\alpha_s(M_Z) = 0.118$
- $\Delta X_{\alpha_s} = (X_{0.120} - X_{0.116})/2$ *is the* α_s *uncertainty computed with two central CTEQ6.6AS PDFs for* $\alpha_s(M_Z) = 0.116$ *and* 0.120

The full proof is given in the paper and backup slides

PDF and α_s uncertainties for $gg \to H$ and $t\bar{t}$ production





Full and reduced fits with variable α_s: cross sections

Process	CTEQ6.6+CTEQ6.6AS				CTEQ6.6FAS
$t\bar{t}$ (171 GeV)	σ_0	$\Delta\sigma_{PDF}$	$\Delta\sigma_{\alpha_s}$	$\Delta\sigma$	$\sigma_0 \pm \Delta\sigma$
LHC 7 TeV	157.41	10.97	7.54	13.31	160.10 ± 13.93
LHC 10 TeV	396.50	18.75	16.10	24.71	400.48 ± 25.74
LHC 14 TeV	877.19	28.79	30.78	42.15	881.62 ± 44.27
$gg \to H$ (120 GeV)	σ_0	$\Delta\sigma_{PDF}$	$\Delta\sigma_{\alpha_s}$	$\Delta\sigma$	$\sigma_0 \pm \Delta\sigma$
Tevatron 1.96 TeV	0.63	0.042	0.032	0.053	0.64 ± 0.055
LHC 7 TeV	10.70	0.31	0.32	0.45	10.70 ± 0.48
LHC 10 TeV	20.33	0.66	0.56	0.87	20.28 ± 0.93
LHC 14 TeV	35.75	1.31	0.94	1.61	35.63 ± 1.70
$gg \to H$ (160 GeV)	σ_0	$\Delta\sigma_{PDF}$	$\Delta\sigma_{\alpha_s}$	$\Delta\sigma$	$\sigma_0 \pm \Delta\sigma$
Tevatron 1.96 TeV	0.26	0.026	0.015	0.030	0.26 ± 0.031
LHC 7 TeV	5.86	0.16	0.18	0.24	5.88 ± 0.26
LHC 10 TeV	11.73	0.33	0.33	0.47	11.72 ± 0.50
LHC 14 TeV	21.48	0.68	0.56	0.88	21.43 ± 0.94
$gg \to H$ (250 GeV)	σ_0	$\Delta\sigma_{PDF}$	$\Delta\sigma_{\alpha_s}$	$\Delta\sigma$	$\sigma_0 \pm \Delta\sigma$
Tevatron 1.96 TeV	0.055	0.0099	0.0044	0.011	0.058 ± 0.012
LHC 7 TeV	2.30	0.085	0.081	0.12	2.32 ± 0.12
LHC 10 TeV	5.08	0.14	0.15	0.21	5.10 ± 0.22
LHC 14 TeV	10.03	0.26	0.27	0.37	10.04 ± 0.41

The full and reduced methods perfectly agree

Summary

CT09MC PDFs

- a reasonably successful attempt to construct PDFs for LO showering programs
- by their design, the PDFs reproduce key LHC inclusive cross sections at NLO
- compatible with existing tunes of MC programs

Summary II

CTEQ6.6AS PDF sets:

- 4 alternative CTEQ6.6 fits for

$$\alpha_s(M_Z) = 0.116, 0.117, 0.119,\ 0.120$$

- sufficient to compute uncertainty in $\alpha_s(M_Z)$ at $\approx$ 68% and 90% C. L., including **the world-average** $\alpha_s(M_Z) = 0.118 \pm 0.002$ as an **input data point**
- **The CTEQ6.6AS** α_s uncertainty should be combined with the CTEQ6.6 PDF uncertainty as

$$\Delta X = \sqrt{\Delta X^2_{CTEQ6.6} + \Delta X^2_{CTEQ6.6AS}}$$

- The total uncertainty ΔX reproduces the full correlation between $\alpha_s(M_Z)$ and PDFs

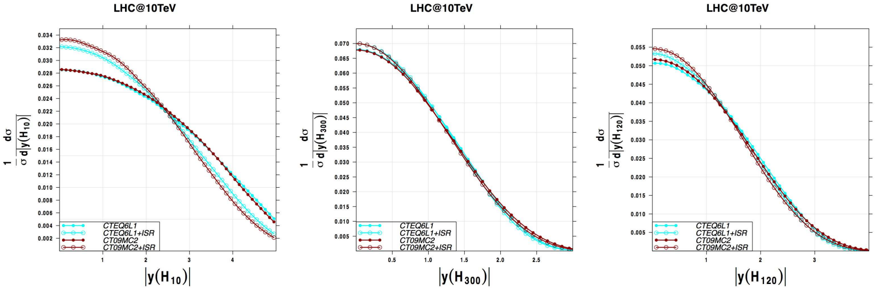
Summary III

- Heavy-quark benchmarking, new statistical methods, and other developments

Backup slides

Effect of parton showering on CT09MC predictions

PYTHIA predictions for $gg \to H$, with and without contributions from the initial-state radiation

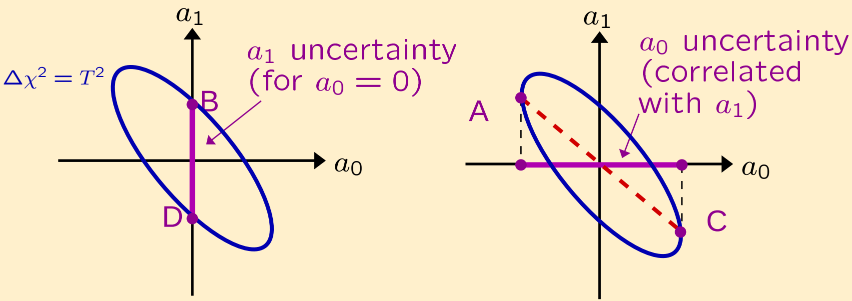


Kinematic showering effects are mild, compared to the PDF dependence, for invariant masses $\gtrsim 100$ GeV

Quadrature theorem for 2 parameters

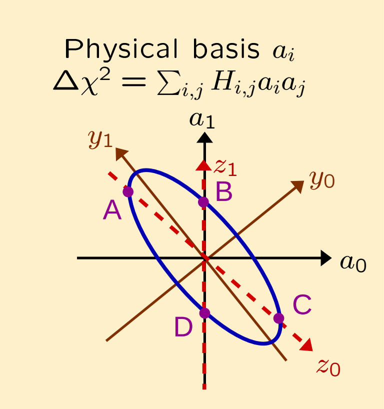
Physical basis a_i

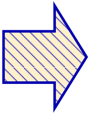
$$\Delta\chi^2 = \sum_{i,j} H_{i,j} a_i a_j$$

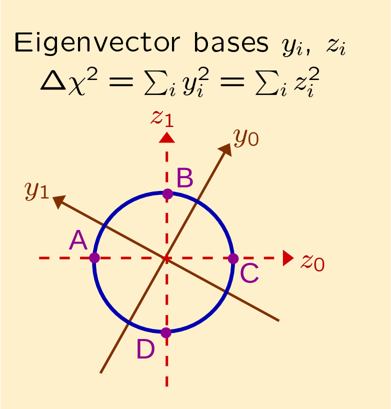


$$\Delta X_1^2 = \frac{1}{4}\left(X(B) - X(D)\right)^2 \qquad \Delta X_0^2 = \frac{1}{4}\left(X(A) - X(C)\right)^2$$

Quadrature theorem for 2 parameters, cont.



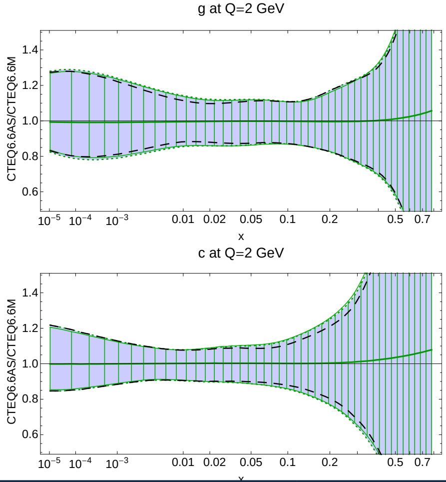




$$\Delta X^2 = \frac{1}{4}\left[(X(A) - X(C))^2 + (X(B) - X(D))^2\right]$$
$$= \Delta X_0^2 + \Delta X_1^2$$

Our findings

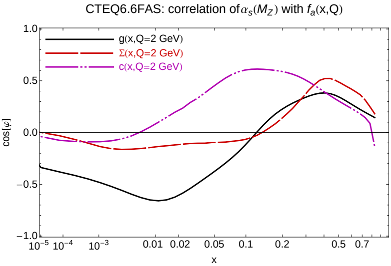
Total PDF+α_s errors ΔX are the **same** when found (a) from a full fit with floating α_s, or (b) by adding ΔX_{PDF} and ΔX_{α_s} in quadrature

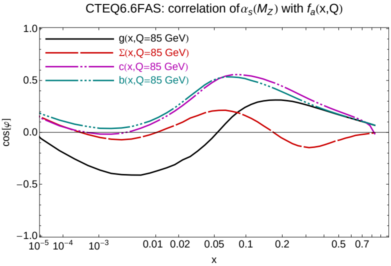


- black – CTEQ6.6 PDF uncertainty
- Blue filled – PDF+α_s uncertainty of the fit with floating $\alpha_s(M_Z)$
- Green hatched – PDF+α_s uncertainty added in quadrature

Correlation cosine between CTEQ6.6FAS PDFs and $\alpha_s(M_Z)$

Based on the method in the CTEQ6.6 paper, PRD 78, 013004 (2008)





$$\cos\varphi = \frac{1}{4\Delta X \Delta Y} \times \sum_{i=1}^{23}\left[\left(X_i^{(+)} - X_i^{(-)}\right)\left(Y_i^{(+)} - Y_i^{(-)}\right)\right]$$

Variations in $\alpha_s(M_Z)$ mostly affect:

- $g(x,Q)$ at $x \approx 0.01$
- $c(x,Q)$ at $x \approx 0.1$
- Singlet quark at $x \approx 0.5$